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THE ESTIMATION OF RUN-OFF IN A MOUNTAINOUS REGION

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THE ESTIMATION OF RUN-OFF IN A MOUNTAINOUS REGION

1. The aim of this paper is to describe the methods used to estimate run-off for the preliminary studies and detailed design of the Snowy Mountains Scheme in south-eastern Australia.

2. The location of the Snowy Mountains is shown on Figure I and a cross section through them on Figure II. The climate of the region is not severe compared with the alpine regions of the other continents. The precipitation varies widely from an estimated maximum of the order of 150 inches per annum to a minimum of 20 inches. In winter and spring there is a predominance of westerly weather with depressions and frontal disturbances moving from west to east. Accordingly the western slopes receive heavy falls of rain and snow which are increased by orographic lifting, while there is a rain shadow to the east. Snow covers the ground for about six months of the year. The summer and autumn are drier, although with the weakening of the westerly circulation, there are occasional intrusions of tropical air and moderate thunderstorm activity; in these months the eastern slopes are favoured. The effects just described are illustrated on Figure II.

3. The essence of the Scheme is the diversion of the Snowy River into the Murray and Murrumbidgee Rivers. By taking advantage of the east-west difference in levels, large quantities of power can be generated as the water is diverted inland. Altogether there will be 9 major dams, 10 power stations, 100 miles of tunnels and 80 miles of aqueducts. The estimated cost of the Scheme, commenced in 1949 and now half completed, is £(A)400,000,000. Annual expenditure has averaged £(A) 15,000,000.

VARIABILITY OF RUN-OFF

4. The variability of run-off in an area greatly influences the planning of its hydrologic network and the estimation of its run-off; in mountainous areas its importance is accentuated because it is usually high. The run-off distribution in the Snowy Mountains illustrates the variation which may occur in a relatively compact and apparently homogeneous area. For example, the measured average annual run-off of a small catchment of 1.8 square miles with an average elevation of 6,300 feet near Mt. Kosciusko was 13.0 feet during the period, 1953-1960. During the same period the run-off only 16 miles to the east was as little as 0.2 feet. Isopleths of estimated average run-off are superimposed on Figure I together with an inset showing the monthly distribution of run-off from the area as a whole. The contribution of the different calendar months to the

annual total may also vary greatly. In order to illustrate this, the monthly run-offs of a number of small catchments with mean elevations at approximately 1,000 feet intervals are shown on Figure IV.

5. The other feature of the variability of run-off is its temporal variability.[2,3] Long term streamflow records of the region should be examined but if these are not available, as is usually the case, precipitation records and other data should be studied. Kraus[4] found that the average annual precipitation of south-eastern Australia during the last 50 years, the period for which streamflow records are available, was about 10% less than that of the overlapping 100 year period. Even a variation in the seasonal distribution of precipitation without any significant trend in the annual average can materially alter run-off, since the losses are very much dependent upon temperature.

PRELIMINARY RUN-OFF ESTIMATES

6. Although long streamflow records provide the only really satisfactory method of determining the run-off from an area, often there are none, or only a few of relatively short duration. In the former case the run-off must be estimated from precipitation by subtracting evapo-transpiration losses, while in the latter the records that are available can be used to derive relationships between precipitation and run-off which can be applied to ungauged areas or used to extend short records. A number of procedures for carrying out this type of investigation have been outlined by Linsley[5] who provides a useful bibliography. Langbein[6] and Penman,[7] among others, also give examples. Elsewhere Langbein[8] has demonstrated how, under certain conditions, long records of precipitation and run-off may be inferred from short records of lake or groundwater levels.

7. The run-off distribution of the Snowy Mountains was first estimated by a committee appointed by the Commonwealth Government in 1947 to investigate the power and irrigation potential of the region. This committee[9] produced a map showing isopleths of average annual run-off based on a relation between recorded streamflow and elevation characteristics and the distance east of the Great Dividing Range. This map was the foundation of the preliminary investigations which determined the general layout and feasibility of the Scheme. When the Snowy Mountains Authority was established in 1949, further detailed

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[2]McDonald, C.C. and Langbein, W.B., Trends in run-off in the Pacific Northwest, Trans. Amer. Geophys. Union, 29, 387-397 (1948).
[3]Williams, G.R., Cyclical variations in world wide hydrologic data, Proc. Amer. Soc. Civil Engrs., 87 No. HY 6, 71-88 (1961).
[4]Kraus, E.B., Secular changes in the rainfall regime of S.E. Australia, Quart. J. Royal Meteor. Soc. 80, 591-601 (1954).
[5]Linsley, R.K., Techniques for surveying surface-water resources, World Meteor. Organ. Tech. Note No. 26, Geneva (1958).
[6]Labgbein, W.B., Hydrologic data networks and methods of extrapolating or extending available hydrologic data, U.N. Flood Control Ser. No.15, Bangkok (1960).
[7]Penman, H.L., The water balance of the Stour catchment, J. Inst. Water Eng. 4, 457-469 (1950).
[8]Langbein, W.B., Water levels as indicators of long-term precipitation or run-off, Int. Ass. Sci. Hydrol. Gen. Assem. Helsinki; Comm. Surface Waters, 517-526 (1960).
[9]Commonwealth of Australia, Diversion and utilization of the water of the Snowy River, Final report of the Commonwealth and States Snowy River Committee (1950).

studies were necessary and this resulted in an expansion of the stream gauging network.

STREAM GAUGING NETWORK

8. The desirability of designing a stream gauging network is now generally recognized; Kohler[10] gives useful advice and references on this question. The growth of the Authority's network is shown on Figure III. The density of the network was governed by the variability of the run-off and the intensity of the proposed development. Ultimately there will be from 60 to 70 diversion points, excluding minor intakes of aqueducts. The network was designed to cover all possible methods of development so that a number of stations were established at locations well removed from the final layout.

9. The almost concurrent investigation and design of the Scheme called for the production of data from the gauging stations as soon as possible. The manner in which this was achieved is described elsewhere.[11,12] After completion of the investigation of a project, the gauging stations associated with it have been discontinued except those required for operational purposes. Thus, in practice, the gauging station network has been operated along very similar lines to Langbein's[13] concept of base and satellite stations. Typical short term records have been from five to eight years.

FINAL ESTIMATES OF RUN-OFF

10. The records from the network just described have provided data for the final investigations which determined exact dimensions. They have all been extended back to 1905 because the records of the basic long term stations are available from that year, and because extension to 1848 (by correlation with rainfall) of the records of the two major rivers draining the area showed that the period from 1905 could be regarded as conservative. The time unit adopted has been the calendar month since this was the most suitable unit for the problems of storage design and operation which have been encountered. For the small diversions daily flows have been required but these estimates are not discussed in this paper.

11. Precipitation data have not been used directly in the extension, firstly, because the streamflow data have been adequate, and secondly, because with a high proportion of the winter precipitation occurring as snow which does not appear as run-off till a few months later, the precipitation of a given month is not related to its run-off. An associated factor is the low accuracy of precipitation measurements at exposed mountain sites where wind effects cause a marked reduction in the catch of snow and even rain.[14]

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[10] Kohler, M.A., Design of hydrological networks, World Meteor. Org. Tech. Note No. 25, Geneva (1958).
[11] Pender, E.B., Walsh, D.T. and Anderson, D., Hydrology in the Snowy Mountains area, J. Inst. Engrs. Aust. 28, 51-66 (1956).
[12] Leech, T.D.J., The training and use of sub-professional staff, J. Inst. Engrs. Aust. 31, 247-259 (1959).
[13] Langbein, W.B., How long should gauging stations be operated? Proc. 22nd Ann. Meet. Western Snow Conf. 19-26, (1954).
[14] Weiss, L.L., and Wilson, W.T., Precipitation gauge shields, Int. Assoc. Sci. Hydrol., Gen. Assem. Toronto, I, 462-484 (1958).

CORRELATION TECHNIQUES

12. The techniques used have been described by Brown.[15] For convenience, they were grouped into five main classes, each summarized below.

13. Simple correlation: This term denotes the case in which a single curve is used to define the relationship between two run-off variables. The curve may be fitted by inspection, by least squares analysis or by some graphical technique such as that put forward by Langbein and Hardison.[16] Logarithmic transformation has been found useful. The main weakness of the method is that no attempt is made to account for the natural variation in the relationship.

14. Parametric correlation: This denotes a method in which the data are first grouped according to the value of a physical parameter and a separate relationship is then defined for each group. The parameters applied have included the relative distribution of precipitation over the catchments, antecedent conditions, the season of the year, and temperature. This method corrects a number of the weaknesses of the simple correlation, particularly its failure to reproduce individual months accurately and its susceptibility to error when the period on which the correlation is based is not hydrologically representative of that to which it is to be applied. It is important, however, that there are sound physical reasons behind the choice of parameters and that there is an adequate sample size in each of the sub-groups. When rainfall parameters are used corrections to the monthly totals may be necessary.[15]

15. Multiple correlation: This denotes correlations in which the dependent variable is related to a number of independent variables by multiple regression analysis. Partial correlation analysis has been used extensively in the selection of variables and testing of their significance. The whole approach is very flexible since it is possible to fit either linear or curvilinear relationships, transform the data, or stratify it into groups. Its main advantages are that the analysis can be carried out in a completely objective fashion using recognized statistical techniques and that the computations are easily handled by electronic computers. An example of the method is given by Sharp and others.[17] The discussion of this paper by Riggs[18] is valuable in that it stresses the need for significance tests on the variables selected and gives some useful comment on the principles of the procedure.

16. Seasonal correlation: This is a particular case of a parametric correlation in which the data are stratified according to the calendar month or season of the year and then each group is treated separately by one or other of the techniques already outlined. It is important that the seasonal effect is real and that tests are made to see if the relationships derived from the different groups are significantly different from each other. An investigation to extend the record of the Swampy Plain River is given as an example. In this case, the

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[15] Brown, J.A.H., Streamflow correlation in the Snowy Mountains Area, J. Inst. Engrs. Aust. 33, 85-95 (1961).
[16] Langbein, W.B., and Hardison, C.H., Extending streamflow data, Proc. Amer. Soc. Civil Engrs. 81, Paper No. 826 (1955).
[17] Sharp, A.L., et al, Application of the multiple regression approach in evaluating parameters affecting water yields of river basins, J. Geophys. Res. 65, 1273-1286 (1960).
[18] Riggs, H.C., Discussion on "Application of the multiple regression approach etc." by Sharp, A.L. et al, J. Geophys. Res. 65, 3509-3511 (1960).

run-off of four surrounding catchments were tested as independent variables in a multiple regression analysis and relationships computed for each month separately. The variation of the gross correlation coefficients and standard errors is shown on Figure V. It is interesting to note that the most highly related variable changes three times during the year.

17. There are some useful methods which do not fall readily into the previous categories, for example, the method of deviations and the coaxial method described by Linsley, Kohler and Paulhus [19]

COMPARISON OF METHODS

18. In order to illustrate the practical effect of the different methods of extension, an example used by Brown[15] is given. Four methods were applied to a common five year period of record of the Snowy River at Island Bend and the Snowy River at Jindabyne. The methods were simple correlation with a line fitted by least squares, simple correlation (logarithmic) with a line fitted by the technique of Langbein and Hardison,[16] seasonal correlation, and a parametric correlation. The derived relationships were applied to extend the record at Island Bend by 43 years. The monthly values obtained were then used to prepare residual mass curves to determine the differences in the storages which would have to be provided to give varying degrees of regulation if the different sets of data were used. From Figure VI, it can be seen that although the average annual values are very similar, there is a significant difference in the sizes of the storages.

19. Even if a method does accurately estimate values over a short period, large errors can still arise in estimates of average annual run-off unless the period on which the relationship is derived is hydrologically representative of that to which it is to be applied. Periods of two years or even longer can easily be characterized by a dominant weather influence which departs strongly from the normal and gives a distribution of streamflow not typical of average conditions over a long period of time. As an example, the monthly run-off of the Crackenback River was related to that of a nearby catchment, the Swampy Plain River. The common period of record of 12 years was divided into three groups of four years and lines fitted separately to each as shown on Figure VII. In spite of the large scatter, the period, 1949-1952, would predict significantly higher average run-off than the other periods. The effect of these wide differences could only be avoided by the introduction of further variables or by the use of some form of parametric correlation.

CONCLUSIONS

22. From the experience which has been acquired a summary is made below of some matters which are considered to be of importance:
(a) The gauging station network should be planned with the concept of base and satellite stations in mind.
(b) A number of small index catchments at different elevations and giving good geographical coverage can provide very useful data.
(c) When estimating run-off, either average annual or monthly, it is desirable to consider the whole area and not small portions in isolation.
(d) In any extension of records, it is most important that the

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[19] Linsley, R.K., Kohler, M.A. and Paulhus, J.L.H., Applied Hydrology, McGraw - Hill Book Co. Inc., New York, 645-655 (1949).

underlying physical basis of any relationship is sound and that it is not applied to a period for which it is not representative.

(e) Tests should be applied to evaluate the significance of the variables selected in any streamflow correlation.

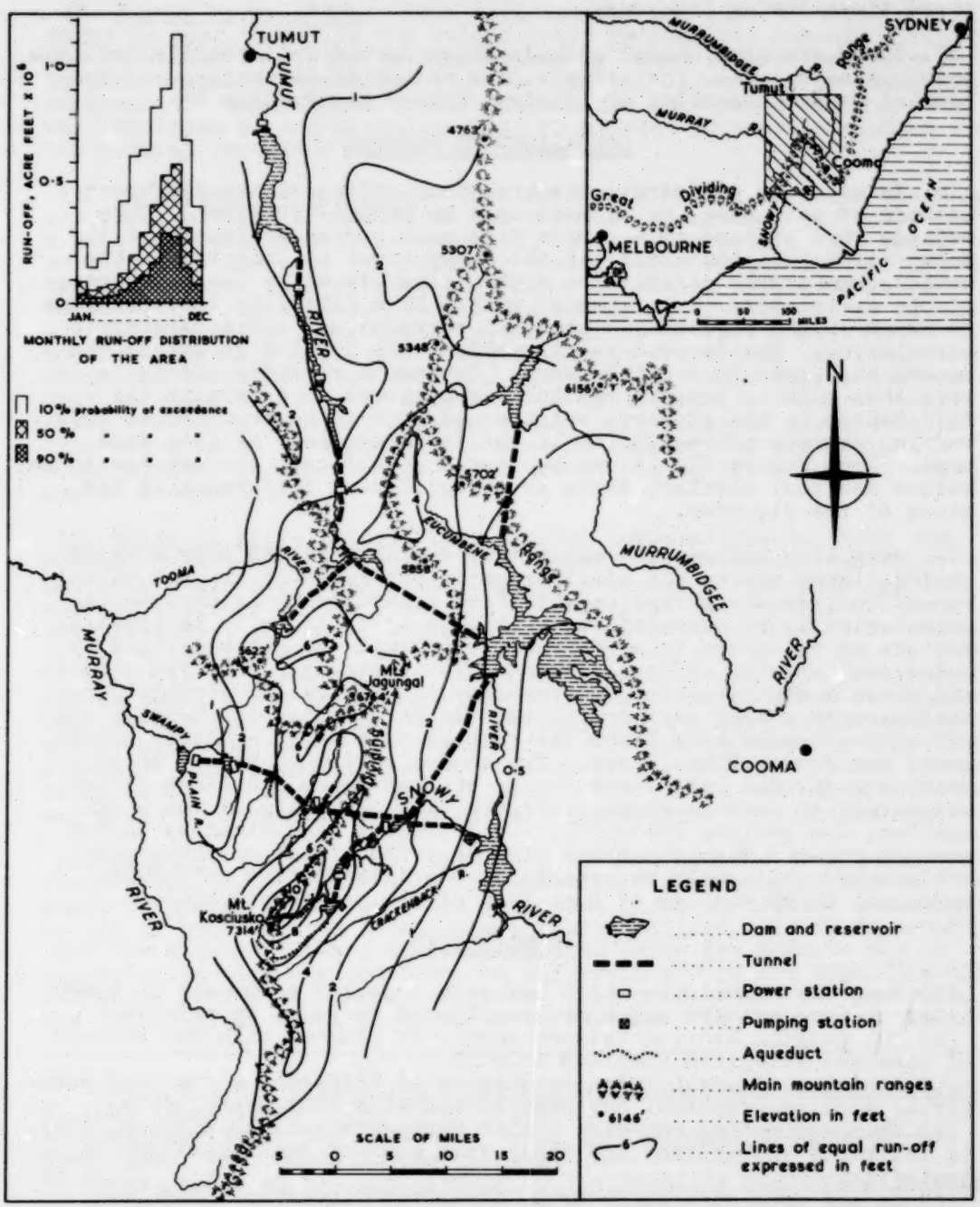


Fig. I. - Location map with details of Snowy Mountains Scheme and lines of equal run-off.

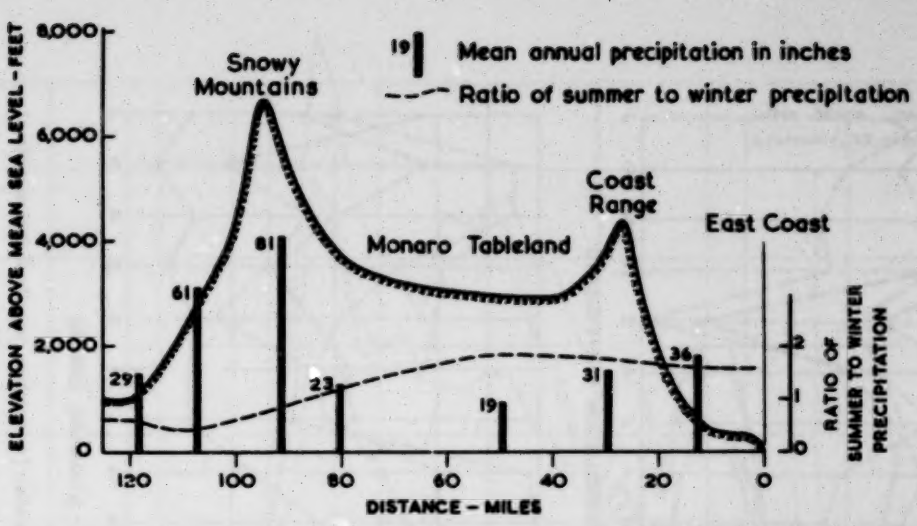


Fig. II - Generalized East-West cross section at latitude S 36° 09' (through Mt. Jagungal).

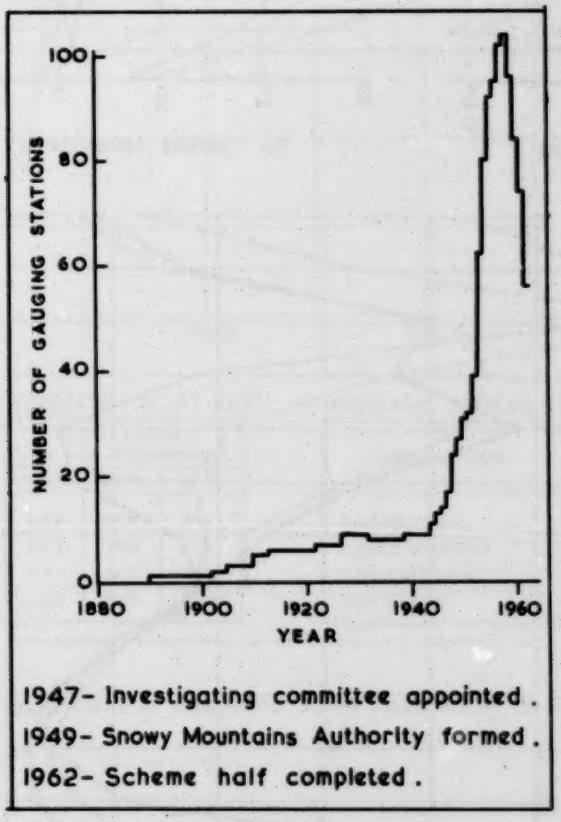


Fig. III - Variation in number of gauging stations

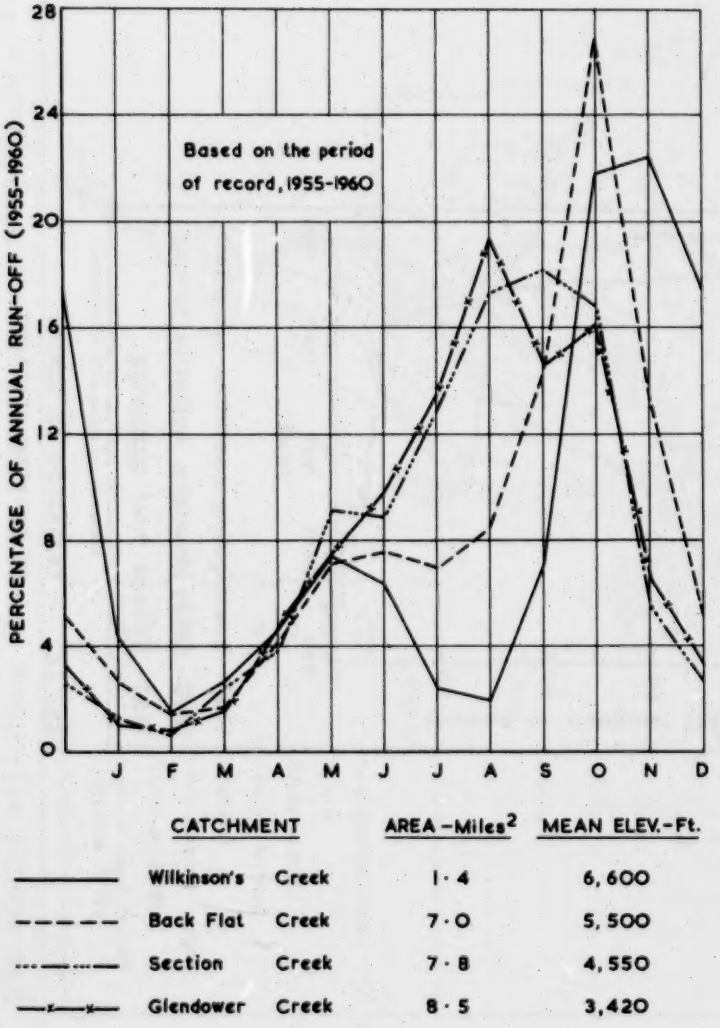


Fig. IV - Variation of run-off with elevation

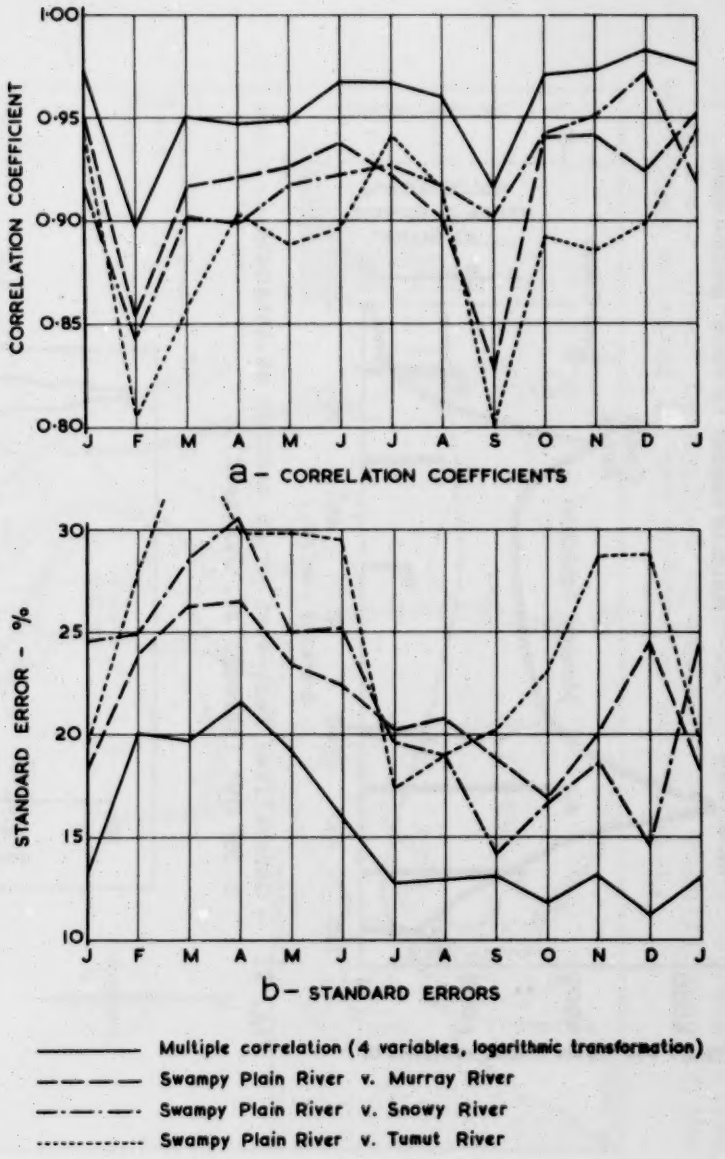
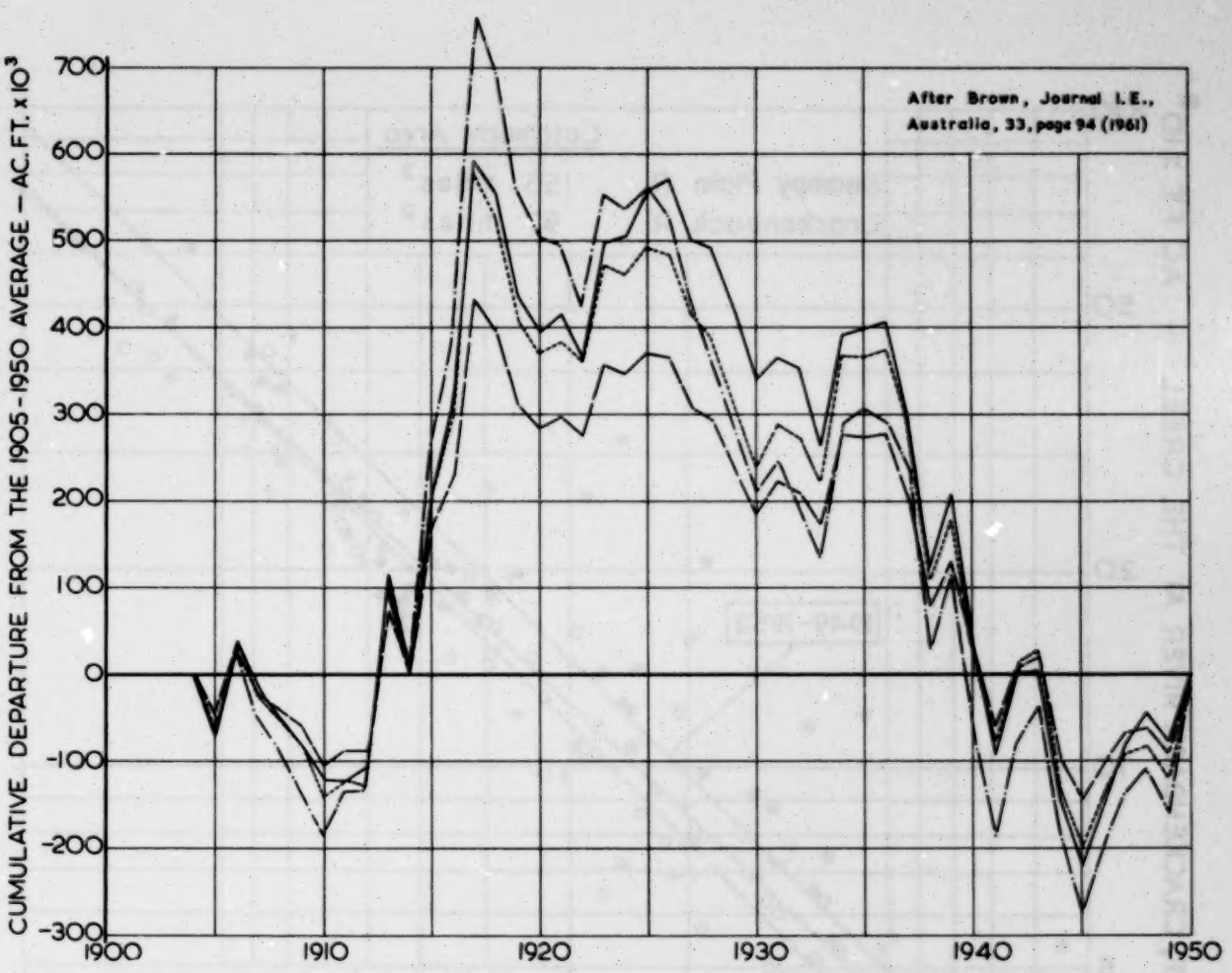


Fig. V - Example of seasonal correlation using multiple regression analysis



STORAGE REQUIREMENTS – AC. FT. x 10^3

CORRELATION	REGULATION – % OF 1905-1950 AVERAGE		
	100 %	90 %	85 %
PARAMETRIC	804	355	271
LEAST SQUARES	578	186	112
LOGARITHMIC	779	310	227
SEASONAL	1027	290	147

AVERAGE ANNUAL DISCHARGE — (1905-1950)

CORRELATION	DISCHARGE (AC. FT. x 10^3)	LEGEND
PARAMETRIC	303·1	———
LEAST SQUARES	296·3	———
LOGARITHMIC	298·2	- - - - -
SEASONAL	311·4	—·—·—

Fig. VI – Residual mass curves computed from data from different correlations

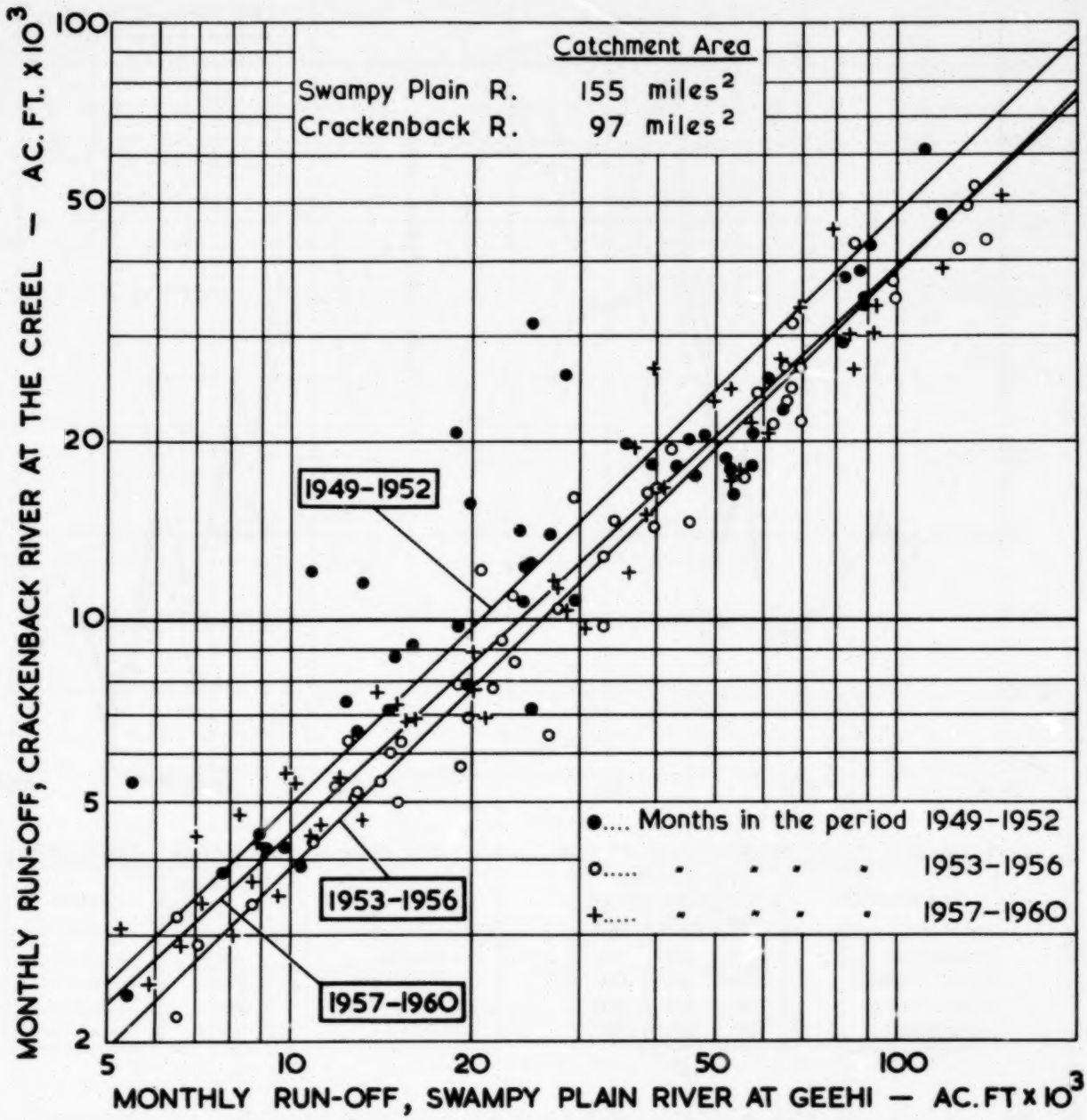


Fig. VII - Variation in run-off relationship curves fitted to successive four year periods

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